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***Abstract*—Parkinson's disease (PD) is a widespread neurodegenerative disorder characterized by the loss of dopaminergic neurons from the substantia nigra, causing bradykinesia, tremors, rigidity, and postural instability. In this paper, we present a differential microwave imaging study (MWI) for early-stage PD monitoring that uses the dielectric properties of the basal ganglia, particularly the thalamus. The simulations are carried out using two scenarios: one is based on studying the sensitivity of a realistic human head model. The other is the study of differential microwave imaging to monitor the PD based on the dopamine level changes in the basal ganglia. The MWI system contains 24 printed flexible antennas with a custom-made matching medium covering the head model. The obtained results demonstrate that small variations in dielectric properties within the human head, in particular the thalamus, can be detected, which can be used to monitor Parkinson's disease in a very early stage.**

I. Introduction

In the past 25 years, Parkinson's Disease (PD) has doubled in prevalence, according to the World Health Organization (WHO), with more than 8.5 million people suffering from the disorder in 2019, with an increase of 81% and 329,000 deaths (a rise of more than 100% since 2000) [1].

The PD is widely studied based on different markers such as the tremors, brain activity, or the dopaminergic neurons level within the brain [2] where the average property of the affected zone changes gradually with time, leading to a progressive stage of the disease.

In this paper, the PD is modeled within the basal ganglia, specifically in the thalamus [3]. To validate the imaging capability of identifying small changes in the dielectric properties, a realistic human head containing skin, fat, skull, gray and white matter, cerebrum, ventricle, and thalamus is used. The validation is performed in two main steps, first a sensitivity study of the system to the small changes in dielectric properties associated with the PD using the system in [4], and second through the differential MWI that allows dealing with small changes of the medium studied using the multi-frequency scanning for high-resolution images.

This paper is organized as follows: starting with an electromagnetic (EM) modeling of the PD in Section II. In Section III the anatomy of the human head will be presented with different parts of the brain model. The results for the system sensitivity to PD, as well as differential imaging, will be discussed in detail in Section IV. Finally, a conclusion and future work related to the results obtained are presented in Section V.

II. Electromagnetic (EM) Modeling Of Parkinson's Disease

Dopamine (DA), the small molecule 3,4-dihydroxyphenethylamine [5], is a basic neurotransmitter that mediates a variety of central nervous systems, such as motor control, cognition, memory, or the endocrine modulation signals. It is also the precursor of hormones, playing a critical role in many neural functions. Movement control is accomplished by complex interactions among various groups of nerve cells in the central nervous system. One important group of neurons is located in the substantia nigra in the ventral midbrain. Nigral neurons give rise to an extensive network of axonal processes that innervate the basal ganglia, establishing predominantly symmetrical synapses with dendritic spines. DA is released by neurons of the substantia nigra to communicate with neurons of the basal ganglia. Abnormal levels of dopamine [6] are associated with severe human psychiatric disorders and neurodegenerative diseases, such as schizophrenia, depression, or PD [5]. Loss of dopaminergic neurons in the brain zone substantia nigra is the main signature of PD, where the ordinary concentration of DA in rats and human thalamus [7] results in values of around $20\ ng/mg$ (molar mass of DA $153.2\ g/mol$) or equivalently a variation of 20.10^{-6} for a single frequency. Studies have shown that symptoms of PD develop in patients with a significant loss ($> 50 - 60\%$) [8] of dopamine-producing cells in the substantia nigra.

III. Numerical Modeling of Realistic Human Head

For the validation of the proposed technique, a realistic human head model is used which contains nine homogeneous tissues as shown in Fig.1. The skin defines the contour from the outside, followed by fat, skull, cerebrum, ventricle, and thalamus, which is the targeted zone for the detection of PD while changing the concentration of DA, that directly affects the permittivity within the thalamus. For the EM evaluation, an in-house 3-D full-wave Finite Element Method (FEM)-based solver is used [9].

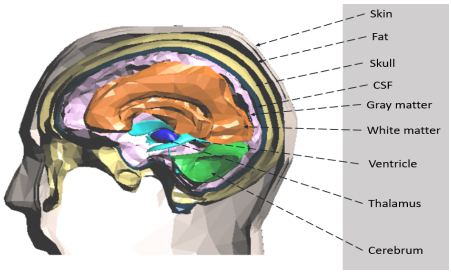

Fig. 1. Realistic human head model

IV. Numerical results

Two levels of results are presented in this section: first, the study of sensitivity within the realistic human head using the system described in [4]. Second, differential imaging is used to identify small variations in dielectric properties using a multi-frequency technique, allowing high-resolution images obtained by combining single-frequency responses.

A. Sensitivity study

To study the responsivity (sensitivity) of the system (using the transmitted signal through the thalamus) to the relative changes into the DA for the proposed microwave monitoring system, the number N_f of independent frequencies [10] and the number of probes [4] N_p have to be considered as a way to amplify by a factor of $N_p \times N_f$ the response of the system. For the proposed setup this factor is $N_p \times N_f = 40 \times 24 \simeq 1000$. In Table I we represent the obtained sensitivity calculated in terms of the contrast of the image defined as the value of the peak of the reconstructed image with respect to the background for DA changes between 10^{-7} to 10^{-3}. It may be seen how the system is able to detect relative changes above 10^{-5} that correspond to 10.10^{-6} (loss of 50% of the DA when PD affects the brain).

TABLE I
SENSITIVITY OF THE SYSTEM TO THE RELATIVE CHANGES INTO THE DA

Relative permittivity change	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}
Image contrast (dB)	0.4	0.7	3	8	14

B. Microwave Imaging Technique

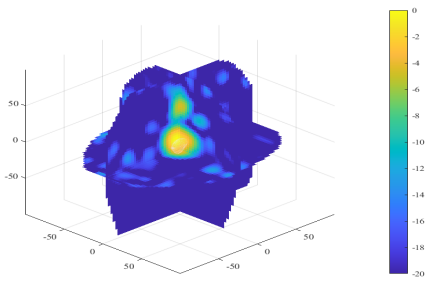

Fig. 2. Normalized differential dielectric contrast amplitude.

Based on the results obtained in Section-IV-A, the MWI technique is applied for $N_f = 40$ independent frequency that results in an amplification of 10^3 as mentioned before. The reconstructed image from the permittivity change associated to a loss of 50% of DA (relative change in permittivity in the order of 10^{-5}) in the thalamus (resulting in changes of $S_{21} \simeq -120dB$) is presented in Fig.2. The results show a good capability on detecting small changes in the dielectric properties of the thalamus that help on monitoring the PD.

V. Conclusion

In this paper, MWI is used to monitor the difference of permittivity related to the PD that is mainly caused by a loss of 50% of dopaminergic neurons that is in the order of 10^{-5}. The results show a good capability on monitoring the PD in an early stage.

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